

Nanoscale CMOS and Beyond: Oxide Electronics - Metal Insulator Transition Switches

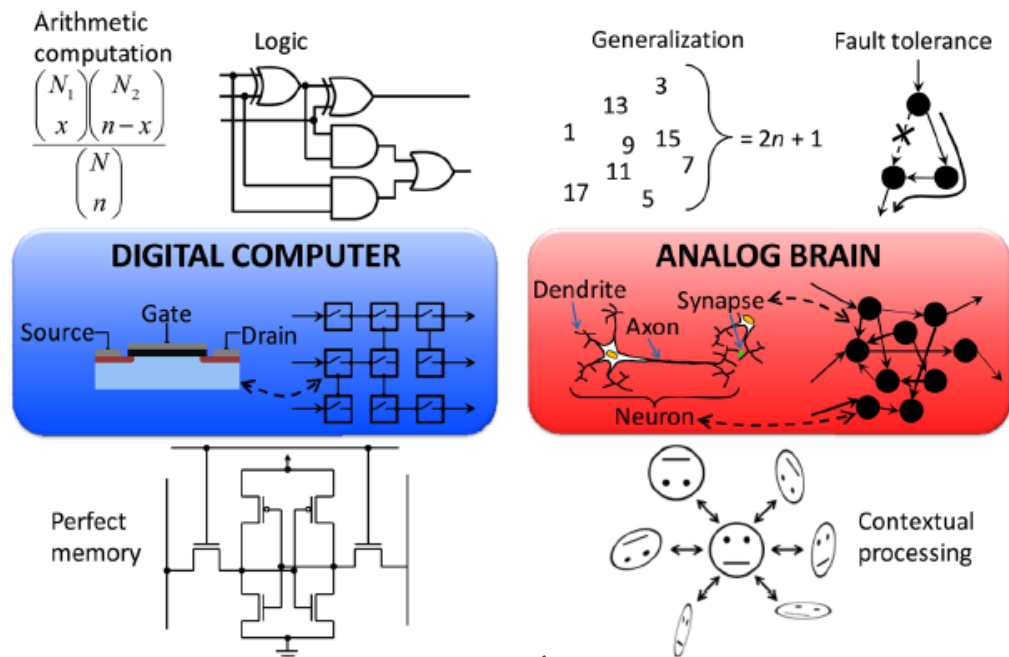
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Outline

- **(Functional/adaptive) oxide electronics: introduction**
- **Metal-Insulator-Transition in Vanadium dioxide (VO_2) material**
- **Technology**
- **Electronics applications:**
 - **Steep slope switches**
 - **Spiking neurons for neuromorphic stochastic machines**
 - **Radio-Frequency devices**
 - **Sensors**
- **Conclusions**

Functional/adaptive oxide electronics

In general terms, adaptive information processing refers to systems in which there is dynamic self-adjustment of system parameters during operation rather than fixed output-to-input relationship. Efficiency increases as the system evolves through self-adjustment. As a basic example, a standard signal filter has a fixed frequency response, but an adaptive filter may sharpen its output function over time across certain frequency ranges in response to input patterns. A common implementation of adaptive computation is in artificial neural networks, which are biologically inspired systems wherein nodes ($\sim$ neurons) send signals between each other through weighted edges ($\sim$ synapses). This is illustrated in the center-right panel of Fig. 2, where nodes are black circles and edges are arrows. The edge weights are independently adjustable and determine the effect of one node on the next. This is in contrast to digital computers, in which binary field-effect transistor (FET) switches are interconnected with fixed weight.



Examples of adaptive/functional oxides

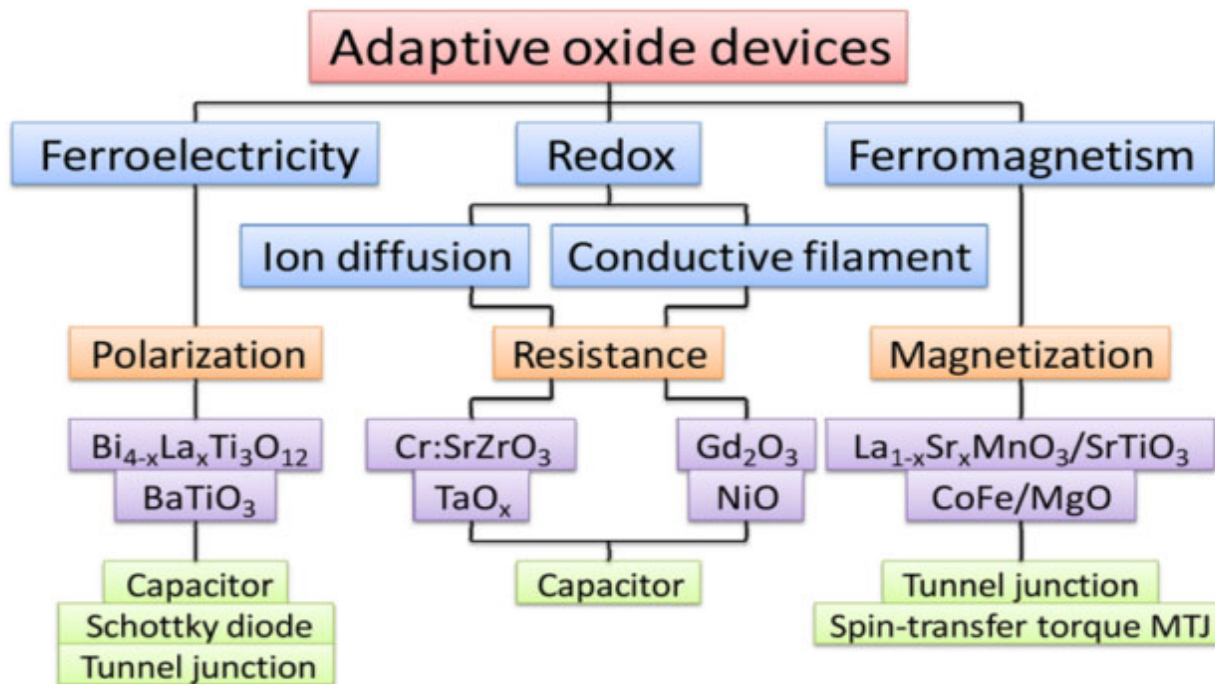


FIG. 5. (Color online) Diagram of adaptive oxide devices surveyed in this review. The levels of the diagram are switching mechanism (2nd), internal state (3rd), representative oxides (4th), and device structures (5th). We discuss devices that have internal state modified by ferroelectricity, ion diffusion, conductive filament formation, and ferromagnetism.

Functional oxides: resistive switching

TABLE I. List of functional oxides used in redox resistive switching devices that may be suitable for adaptive electronics applications. Relevant device properties are specified in the header. Dashes denote that data was not specified in publication. Endurance and retention values do not necessarily reflect device failure limit, only the extent to which respective devices were tested. TE = top electrode and BE = bottom electrode.

Oxide	TE-BE	Multilevel	$\Delta R = R_{Hi}/R_{Lo}$	Switching speed	Retention time(s)	Endurance
Redox resistive						
Binary, bipolar						
CoO	Ta-Pt	-	10^3	20 ns	-	100
Cu _x O	Ti/TiN-Cu	-	10^2	50 ns	10^5 @ 90 °C	600
HfLaO _x	TaN-Pt	-	10^6	10 ns	10^4 @ 27 °C	10^4
HfO _x /TiO _x	TiN-TiN	Y	10^3	5 ns	10^4 @ 200 °C	10^5
TaO _x	Pt-Pt	Y	10^1	10 ns	10^7 @ 150 °C	10^9
TiO ₂	Pt-TiN	Y	10^3	5 ns	10^6 @ 85 °C	10^6
ZrO ₂	TiN-Pt	-	10^1	1 μ s	10^4 @ 27 °C	10^3
Binary, unipolar						
Gd ₂ O ₃	Pt-Pt	-	10^6	-	10^5 @ 85 °C	60
HfO ₂	Pt-Pt	-	10^2	-	10^6 @ 27 °C	140
Lu ₂ O ₃	Pt-Pt	-	10^3	30 ns	10^6 @ 27 °C	300
NiO	Pt-Pt	-	10^2	5 μ s	10^7 @ 27 °C	10^6
TaO _x	Cu-Pt	-	10^2	80 ns	10^6 @ 27 °C	100
TiO _x	Pt-Pt	-	10^4	-	-	25
WO _x	TiN-W	Y	4	300 ns	10^4 @ 100 °C	10^7
ZnO	Pt-Pt	-	10^4	-	-	100
Perovskite, bipolar						
Cr:Ba _{0.7} Sr _{0.3} TiO ₃	Pt-SrRuO ₃	Y	4	0.2 s	10^4 @ 27 °C	10^4
Pr _{0.7} Ca _{0.3} MnO ₃	Ag- YBa ₂ Cu ₃ O _{7-x}	Y	10^2	8 ns	-	10^5
Pr _{0.7} Ca _{0.3} MnO ₃	Al-Pt	-	10^2	20 μ s	10^4 @ 125 °C	10^3
Cr:SrTiO ₃	Au-Au	Y	10	1 ms	8×10^4 @ 27 °C	10^3
Nb:SrTiO ₃	Pt	Y	10^2	50 μ s	10^8 @ 125 °C	10^7
Cr:SrZrO ₃	Au-SrRuO ₃	Y	20	100 ns	10^7 @ 27 °C	-
Cr:SrZrO ₃	Al-LaNiO ₃	-	10^2	500 μ s	10^3 @ 85 °C	-

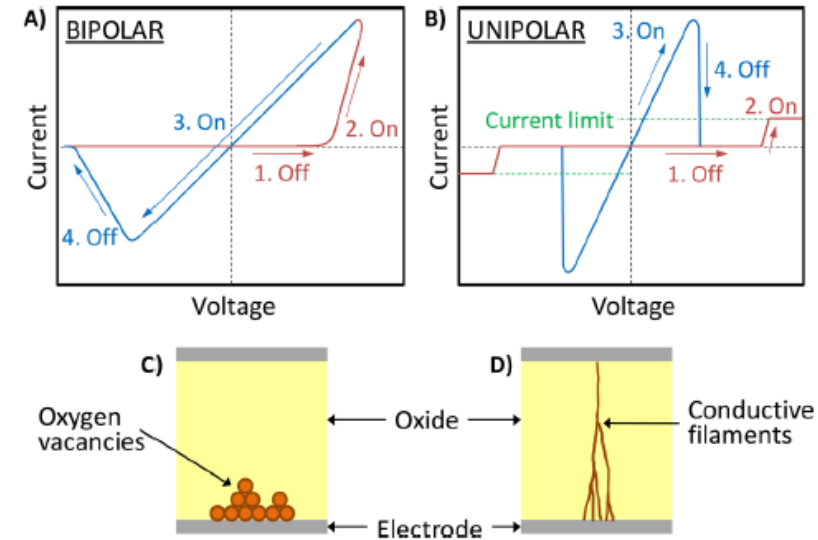


FIG. 6. (Color online) Typical I - V characteristics of (A) bipolar and (B) unipolar resistance switching. In bipolar switching, a device in a high resistance state switches to a low resistance state at high positive voltage and remains in that state until a large negative voltage is applied. In unipolar switching, a device in a high resistance state switches to a low resistance state at high voltage of either polarity and switches back to a high resistance state at lower voltage, again at either polarity. Prospective models of the respective low resistance states are given in (C) and (D). In (C), oxygen vacancy accumulation lowers the Schottky barrier at one electrode. In (D), conductive filaments that span from one electrode to the other effectively shunt the oxide. (Adapted from *Materials Today*, A. Sawa, Resistive switching in transition metal oxides, 11, 28, © 2008, with permission from Elsevier.)

Basics: Mott insulators

- **Definition: What is a Mott Insulator?**
- **Metal that stops conducting under certain conditions (low temperature or high pressure), despite classical theory predicting conduction.**

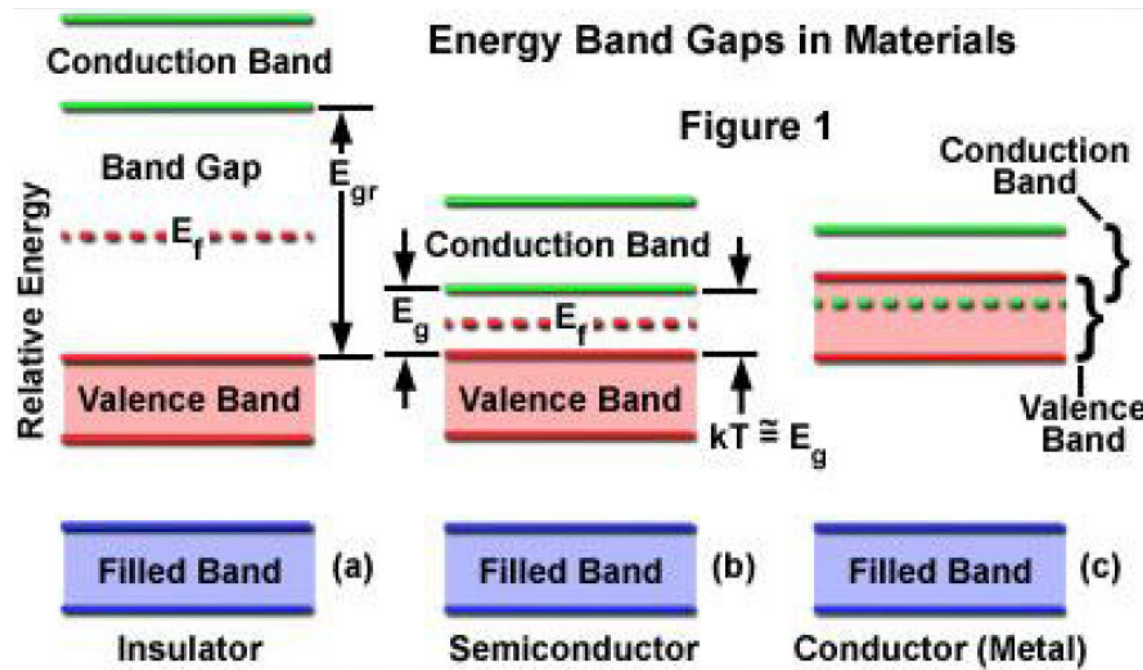
- **Band Gap Theory**
 - Conduction and valence bands
 - Tuning the bandgap
- **Mott Insulators**
 - Origins
 - Theory



- Sir Nevill Francis Mott (30 September 1905 – 8 August 1996) was a British physicist who won the Nobel Prize for Physics in 1977 for his work on the electronic structure of magnetic and disordered systems (amorphous semiconductors).
- Pointed out flaw in central approximation in band theory: *inter-electron forces are not negligible*

Band gap and type of materials

- Band Gap (or lack thereof) responsible for conductors, semiconductors, and insulators.
- Fermi Level: naturally half-way between conduction and valence bands



Mott insulators: theory

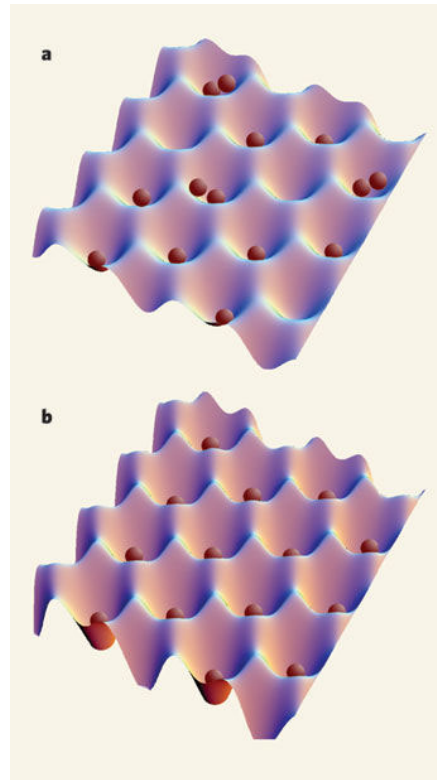
When is a metal not a metal? Steven C. Erwin (Nature, Vol. 441, 2006).

Exception to band theory.

- Materials that **owe their insulating nature to correlations in the motions of different electrons**. These correlations arise from the classical Coulomb repulsion between charge particles. They can be decisive in materials in which the *two competing tendencies of electrons* exist in balance:

- (1) the desire to be spatially localized to minimize Coulomb repulsion
- (2) *the need to be delocalized to minimize the cost in kinetic energy from spatial confinement.*

- Surfaces of semiconductors: electrons are effectively confined to two dimensions. Mott insulators have been created over the past decade on the surfaces of many common semiconductors.



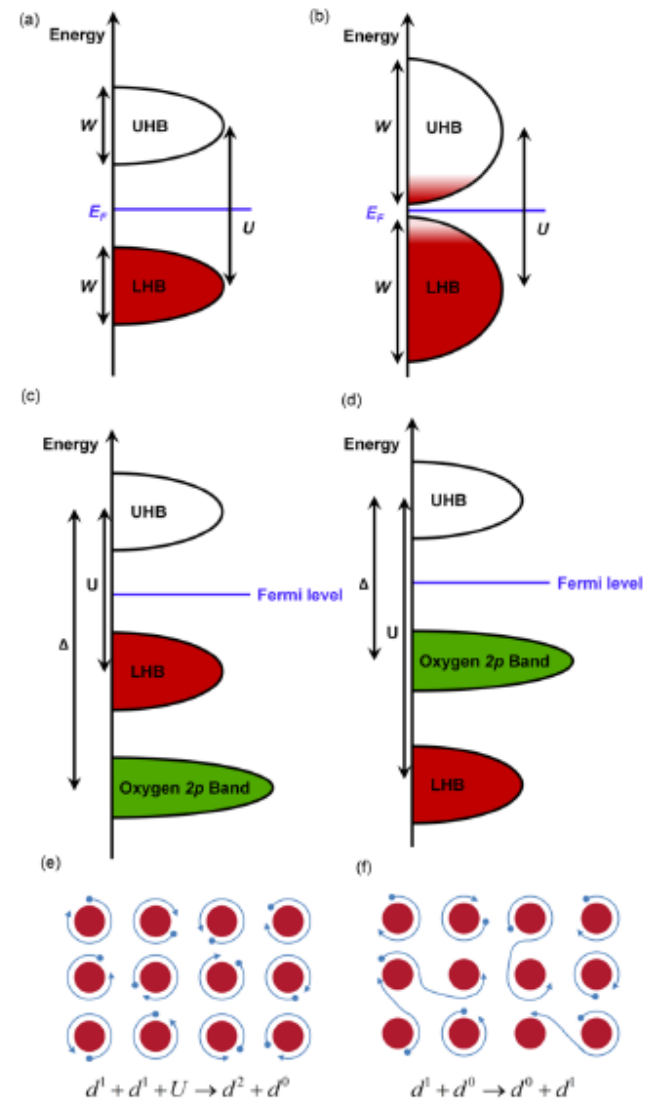
a) The regular potential wells of a normal metallic state of a material with, on average, one electron per atom.

b) If the confining potential is a little stronger (deeper wells), electrons find it harder to delocalize and so do not conduct — despite what the band theory of solids predicts.

The material is a Mott insulator.

Correlated oxides and Metal-Insulator-Transition

- (a) Splitting of a normal band into upper and lower Hubbard band due to electron correlations.
- (b) **Bandwidth controlled metal-insulator transition.** Changing the bandwidth could induce [A METAL-INSULATOR TRANSITION \(MIT\)](#).
- **Oxide Mott insulators could be categorized into two types based on the relative position of the oxygen band and Hubbard bands:**
 - (c) Mott-Hubbard insulator where the oxygen p-band lies under the lower Hubbard band.
 - (d) Charge-transfer insulator where oxygen p-band is in between the lower Hubbard band and upper Hubbard band.
- **Doping holes or electrons into a Mott insulator could lead to a phase transition from insulator to metal.**
 - (e) In undoped Mott insulator ($n=1$), electron hopping leads to formation of a doubly occupied site and increase total energy because of Coulomb repulsion.
 - (f) In a Mott insulator with hole doping ($n<1$), electron hopping does not create doubly occupied sites and system total energy does not change. Electrons could move freely in the matrix and the material becomes metallic.



Oxide Electronics Utilizing Ultrafast Metal-Insulator Transitions

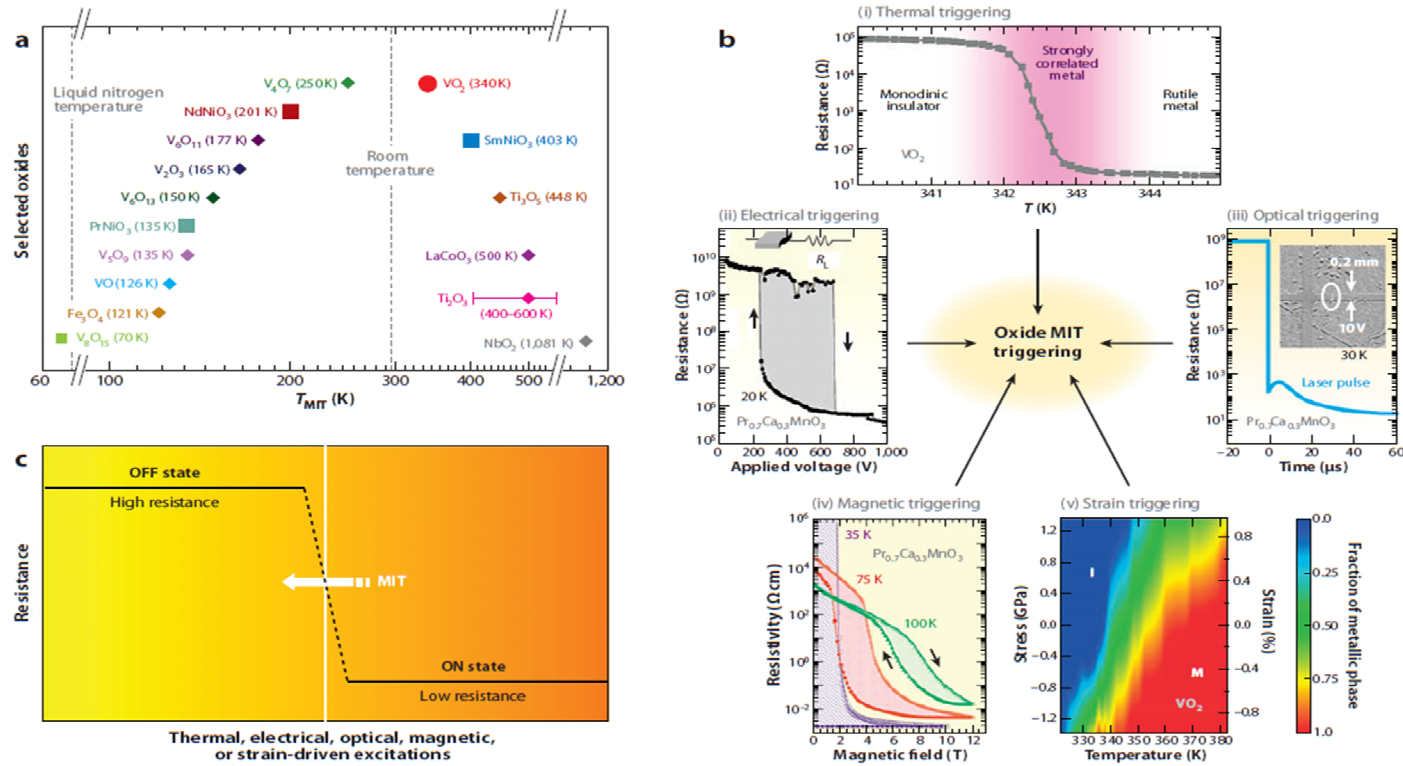


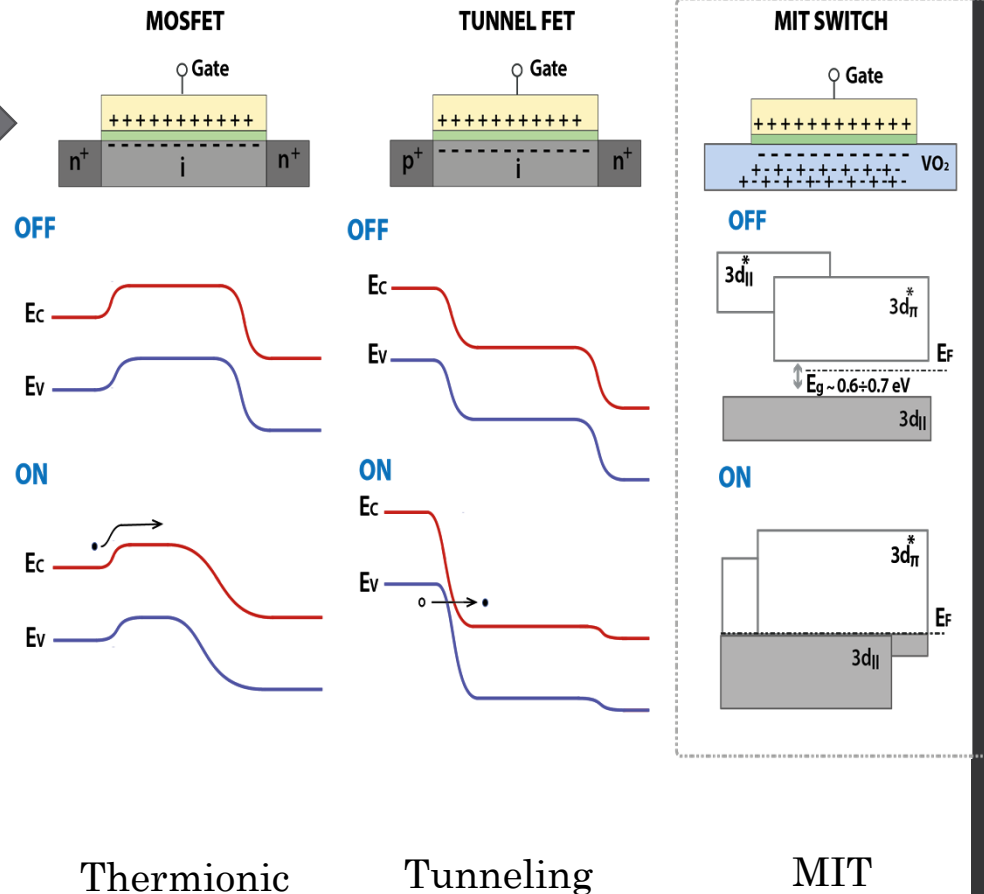
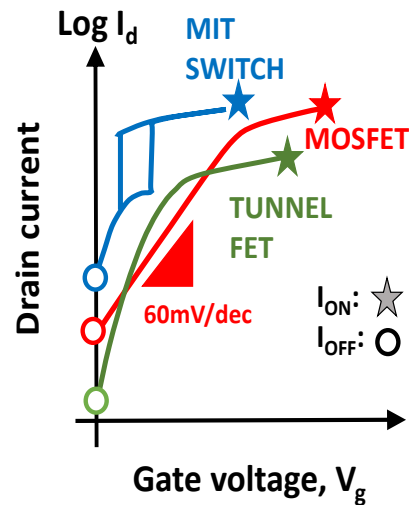
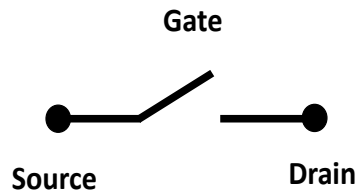
Figure 1

The metal-insulator transition (MIT) switch. (a) MIT temperature (T_{MIT}) of some selected oxides (bulk crystals). External stress or substrate-driven constraints can significantly influence the transition temperature and the resistivity change. (b) MIT-triggering approaches in correlated oxides. (i) Temperature-triggered MIT in VO_2 . (ii) Electrically triggered MIT in $Pr_{0.7}Ca_{0.3}MnO_3$. (iii) Optically triggered MIT in $Pr_{0.7}Ca_{0.3}MnO_3$. (iv) Magnetically triggered MIT in $Pr_{0.7}Ca_{0.3}MnO_3$. (v) Strain/stress effects on MIT in VO_2 . Panel i adapted with permission from Reference 23; panels ii–iv adapted with permission from Reference 19; panel v adapted with permission from Reference 27. (c) Basic concept of utilizing MIT in correlated oxides as a switch, with the high-resistance, insulating and low-resistance, metallic states on both sides of MIT, defined as OFF and ON states, respectively. The switching of the device can be triggered thermally, electrically, optically, magnetically, and by strain drive, corresponding to the MIT-triggering approaches shown in panel b.

MIT steep slope switch

- Three solid-state devices qualitatively compared.
- **Metal-Insulator-Transition** involves a completely different principle:

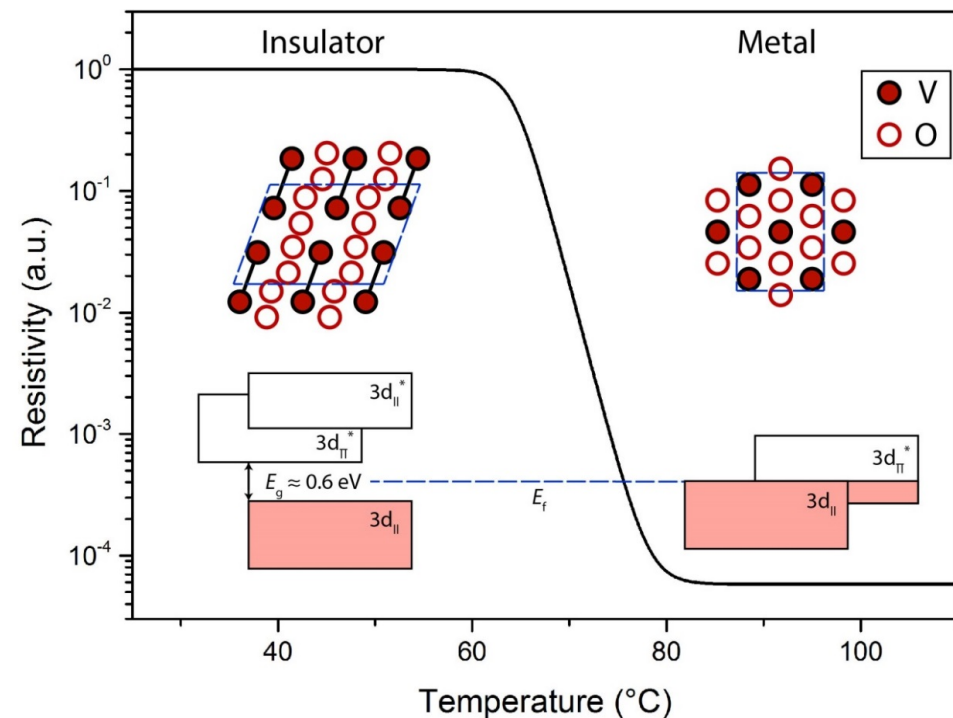
In the so-called MIT-FET or Mott-FET, the gate charge then induces a charge in the channel, which then converts the whole channel type from insulator into a metallic phase.



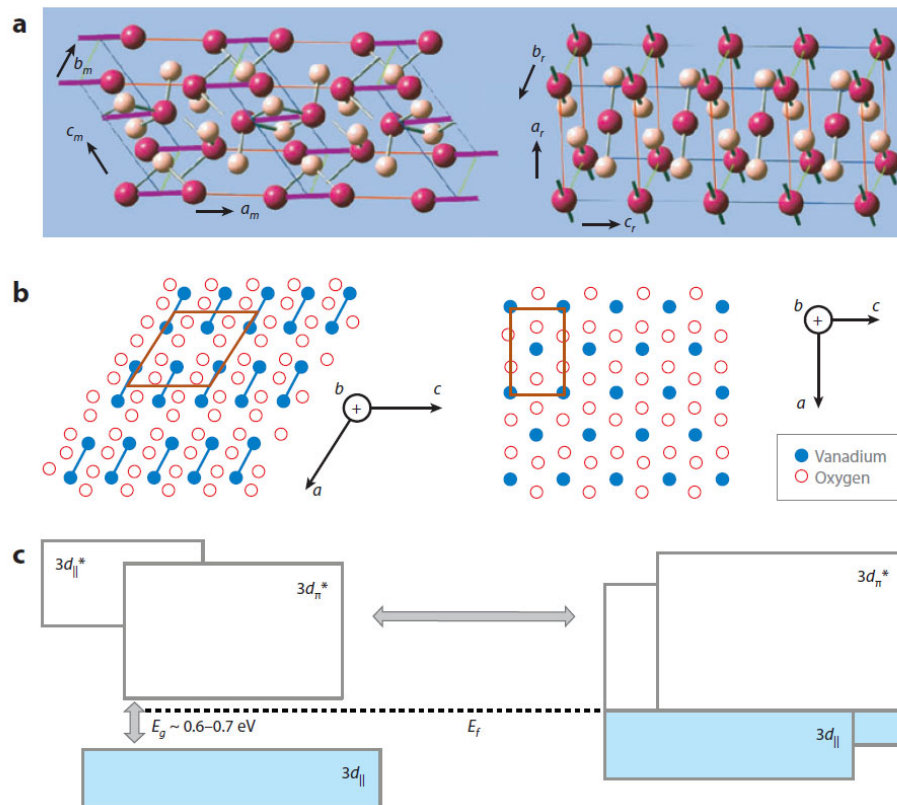
Metal-Insulator Transition (MIT) in Vanadium Dioxide

- Vanadium dioxide (VO_2) undergoes a structural phase transition at $\sim 68^\circ\text{C}$ accompanied by a steep decrease in resistivity.
- The monoclinic phase presents a **bandgap $\sim 0.6\text{ eV}$** .
- The tetragonal phase presents **metallic behavior**.

How to exploit this for integrated electronic (switching) functions?



Bandgap modulation in VO₂



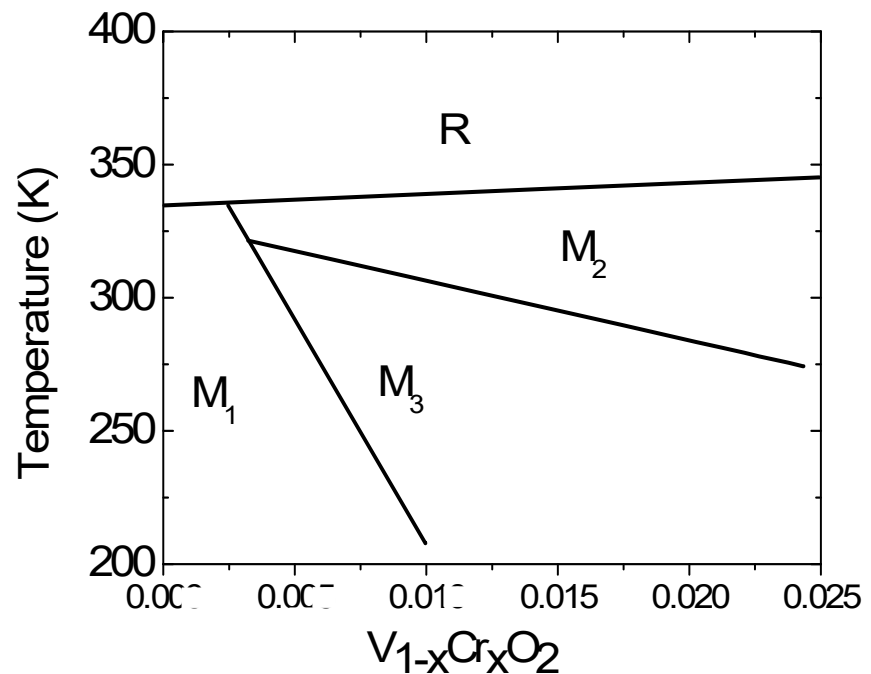
Structure and band diagram of VO₂:

(a, b) Structure change of VO₂ from the monoclinic insulating phase (*M*₁) to the tetragonal rutile metallic phase (*R*) during MIT in (a) a three-dimensional view and (b) a cross sectional view.

(c) Band structure change of VO₂ across the MIT. The left and right panels show the band structures for the insulating and metallic phases, respectively.

Doped VO₂ for bandgap engineering

- The MIT for VO₂ occurs at 340K between the conducting rutile phase and the monoclinic M1-M3 phases .
- VO₂ is of broad interest because its MIT occurs **just above room temperature**. However, the band gap of the insulating phase of VO₂ is only 0.6 eV which, with band edge tailing, means that the on-off resistance range is only about 10⁴ which is insufficient for a FET.
- **Challenge: Doping techniques to increase the band gap in the off state is needed: Mg? Cr? Ge?**

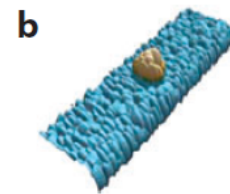


Ultrafast electronic devices and applications with VO₂

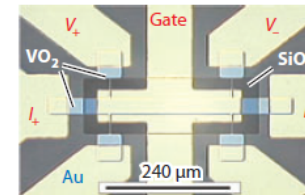
- Recent interest in VO₂ triggered by demonstration of more ‘actuation’ mechanisms.
- Ultrafast switching (~ 10 ns) by electronic excitation.
- Interest in explaining the physics of the MIT.
- Novel device structures and functionalities introduced in multiple fields.

What electronic functions are possible with VO₂?

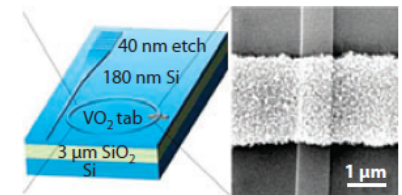
Two-terminal electronic switch
(Section 4.2.1)



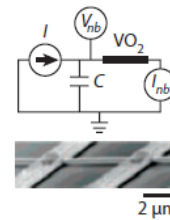
Gated electronic switch (Mott FET)
(Section 4.2.2)



Optical device
(Section 4.3.1)

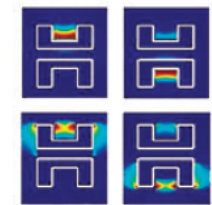


Oscillator
(Section 4.2.3)

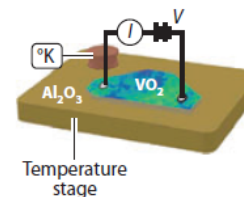


Oxide MIT
devices in
this review

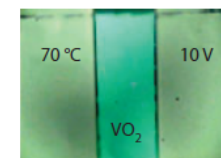
Metamaterial device
(Section 4.3.2)



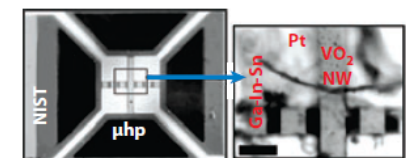
Memristive device
(Section 4.2.4)



Thermal sensor
(Section 4.3.3)



Chemical sensor
(Section 4.3.4)

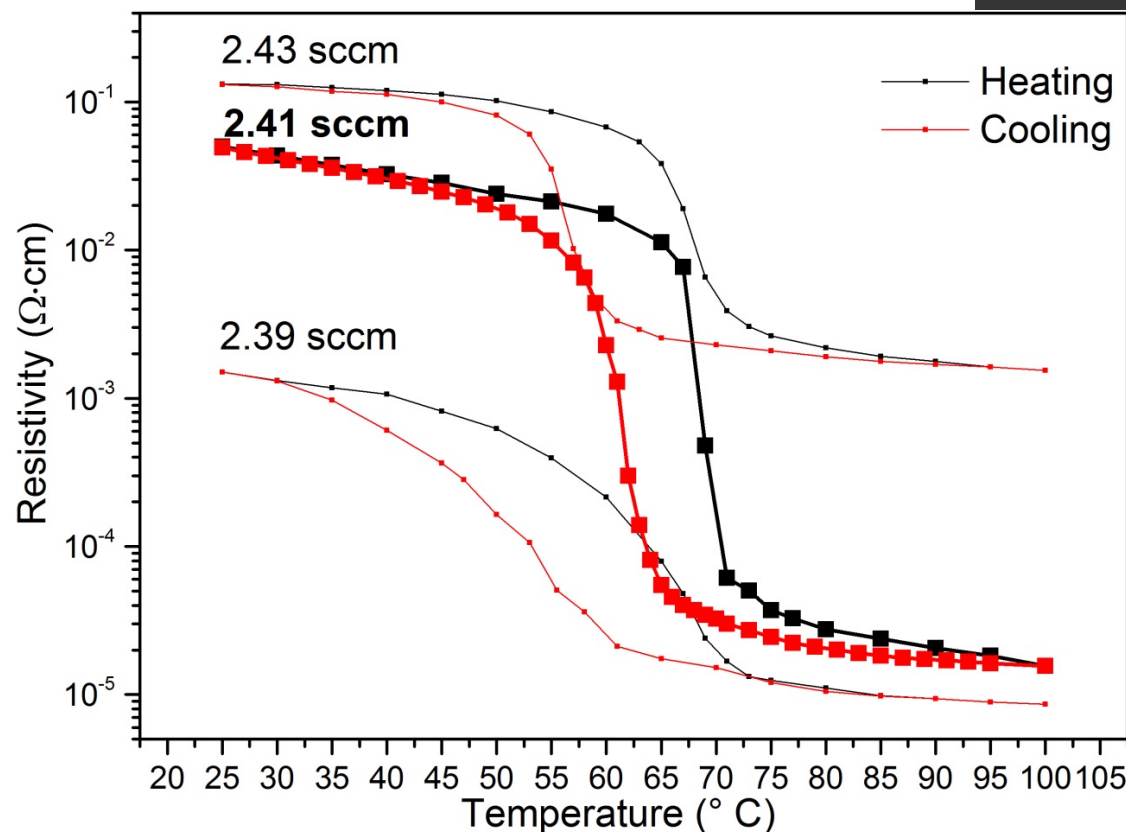
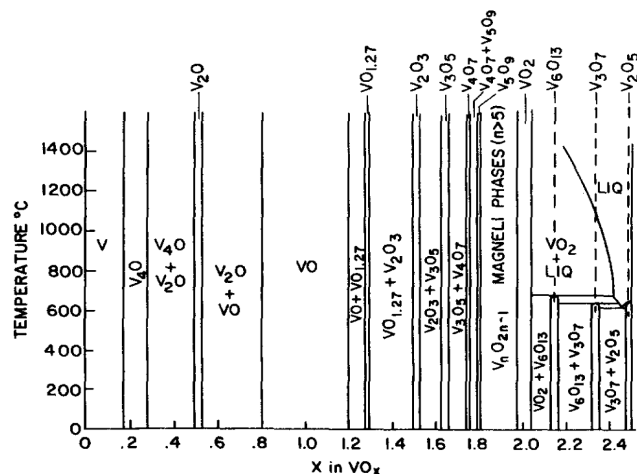


O₂ Growth Optimization Window in VO₂ reactive magnetron sputtering

Sputtering conditions

- Pure V target.
- High T for film crystallinity.
- High-vacuum conditions.
- Deposition rate ~ 3 nm/min
- O₂ flow critical parameter for the VO_x phase.

Phase diagram of vanadium oxides

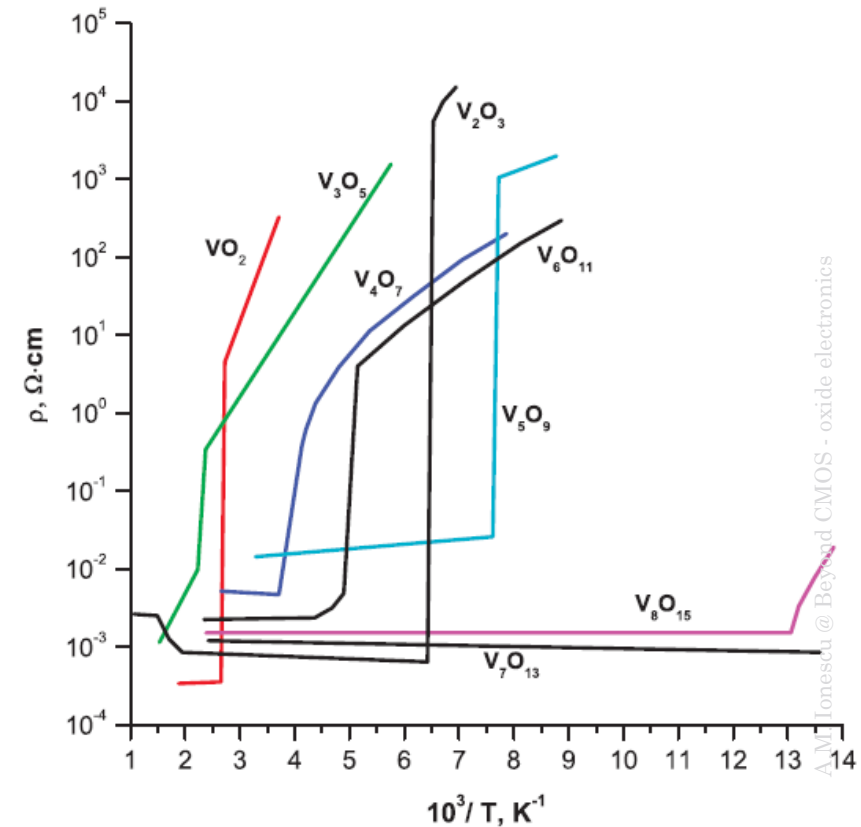


Influence of stoichiometry on transition temperature

TABLE I
VANADIUM OXIDES [47], [48], [54]

n in formula V_nO_{2n-1}	Oxide	T_i , K
(1)	VO	—
(2)	V_2O_3	150
3	V_3O_5	450
4	V_4O_7	240
5	V_5O_9	130
6	V_6O_{11}	170
7	V_7O_{13}	—
8	V_8O_{15}	70
(∞)	VO_2	340
(-6) ^{a)}	V_6O_{13}	150
(-2)	V_2O_5	—

^{a)} V_6O_{13} and V_2O_5 formally correspond to the series V_nO_{2n-1} with negative n , though actually they belong to the Wadsley phases $V_{2n}O_{5n-2}$ [56].



VO₂ 2-terminal diode-like switch

Harvard

EPFL

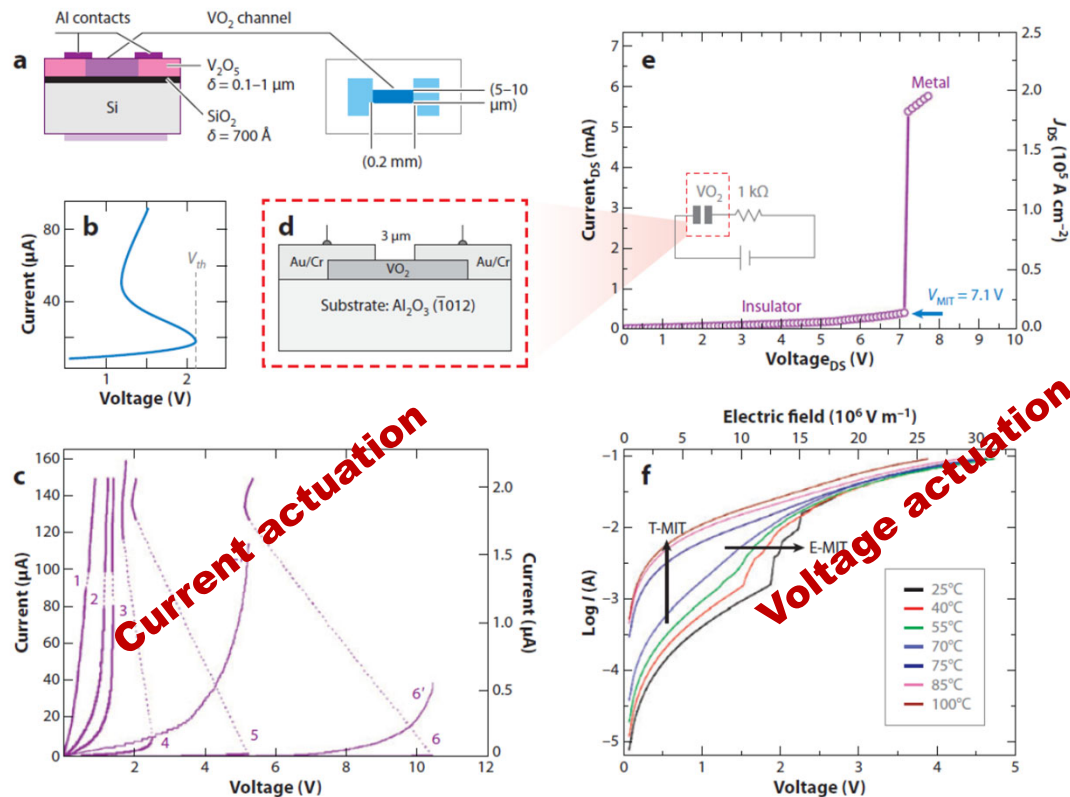
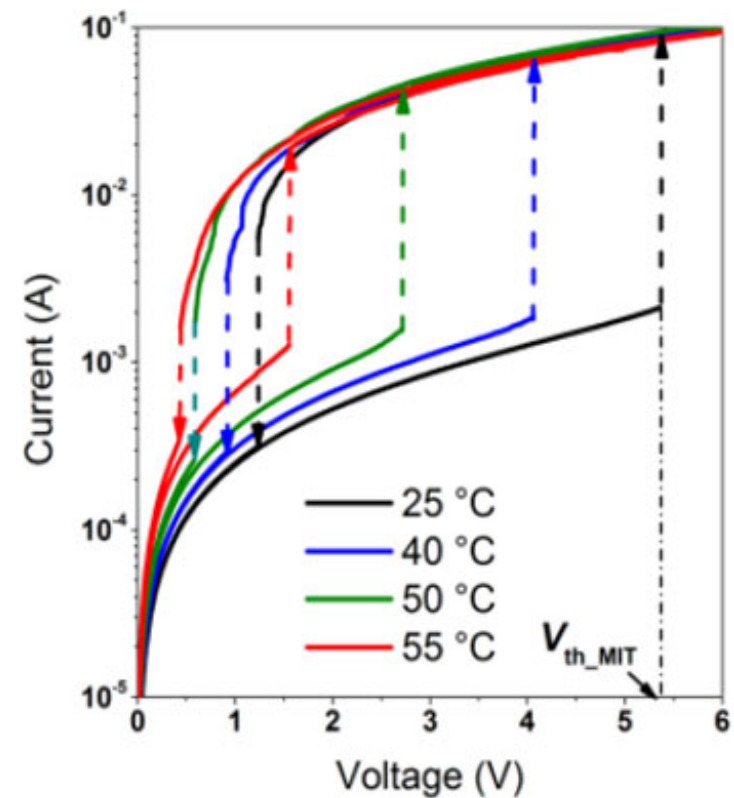
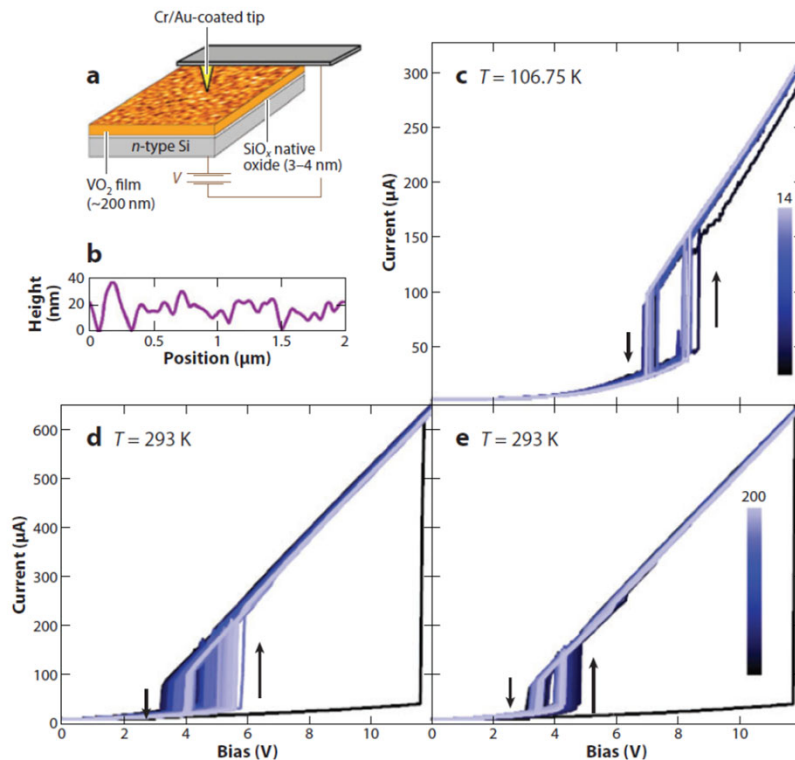


Figure 5

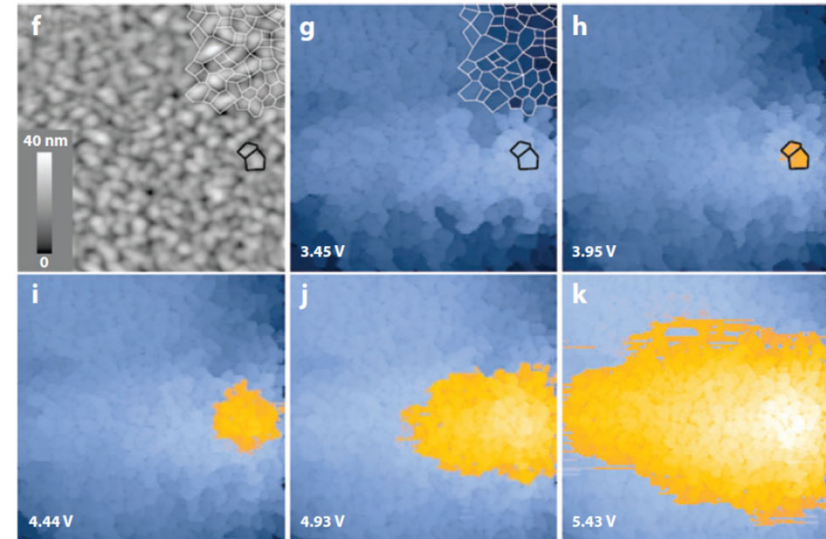


Electrically triggered MIT transition



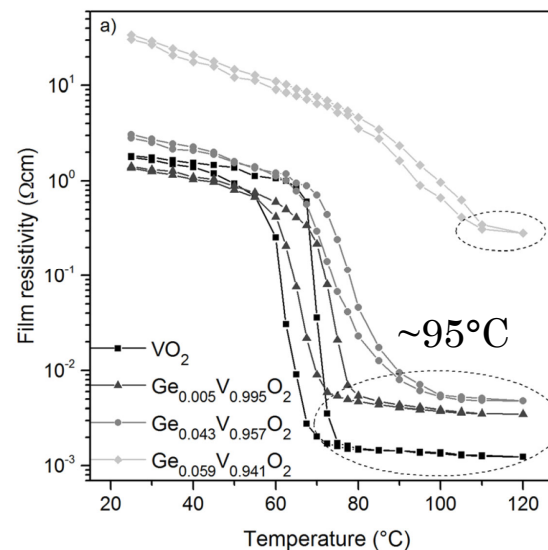
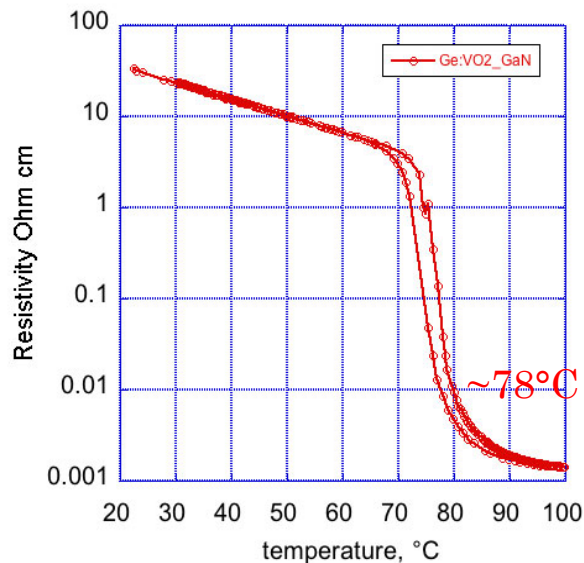
AFM studies of electrically triggered MIT in VO_2 .

(a) Schematic of the AFM tip and the sample geometry. (b) AFM line scan. (c) Fourteen consecutive I - V sweeps at $T = 106.75$ K. (d,e) Two hundred consecutive I - V sweeps at two different representative locations at $T = 293$ K. The color scale bar shows the times of sweep. (f) AFM image showing the surface morphology of the VO_2 thin film. (g–k) Current mapping at different bias voltages. Grain



Ge-doped high temperature transition MIT switch

- donor-like dopants with large ionic radii (W, Mo, and Nb) decrease the transition temperature, while acceptor-like elements of low oxidation state and smaller ionic radii (Al, Cr, Fe) increase the transition temperature
- effect of Ge-doping on the insulator-to-metal phase transition in vanadium oxide and found that the transition temperature can be controlled and be significantly increased upon Ge doping, slightly over 90°C



The spiking biological neuron

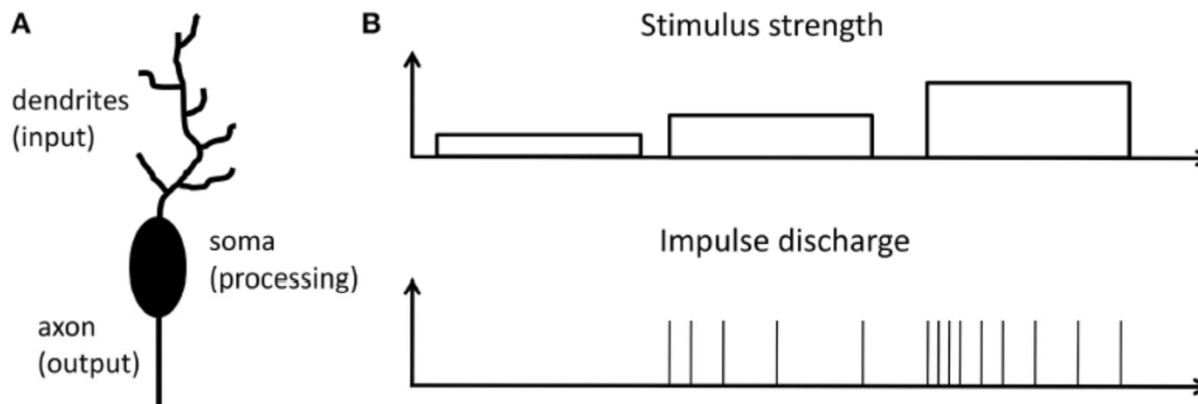
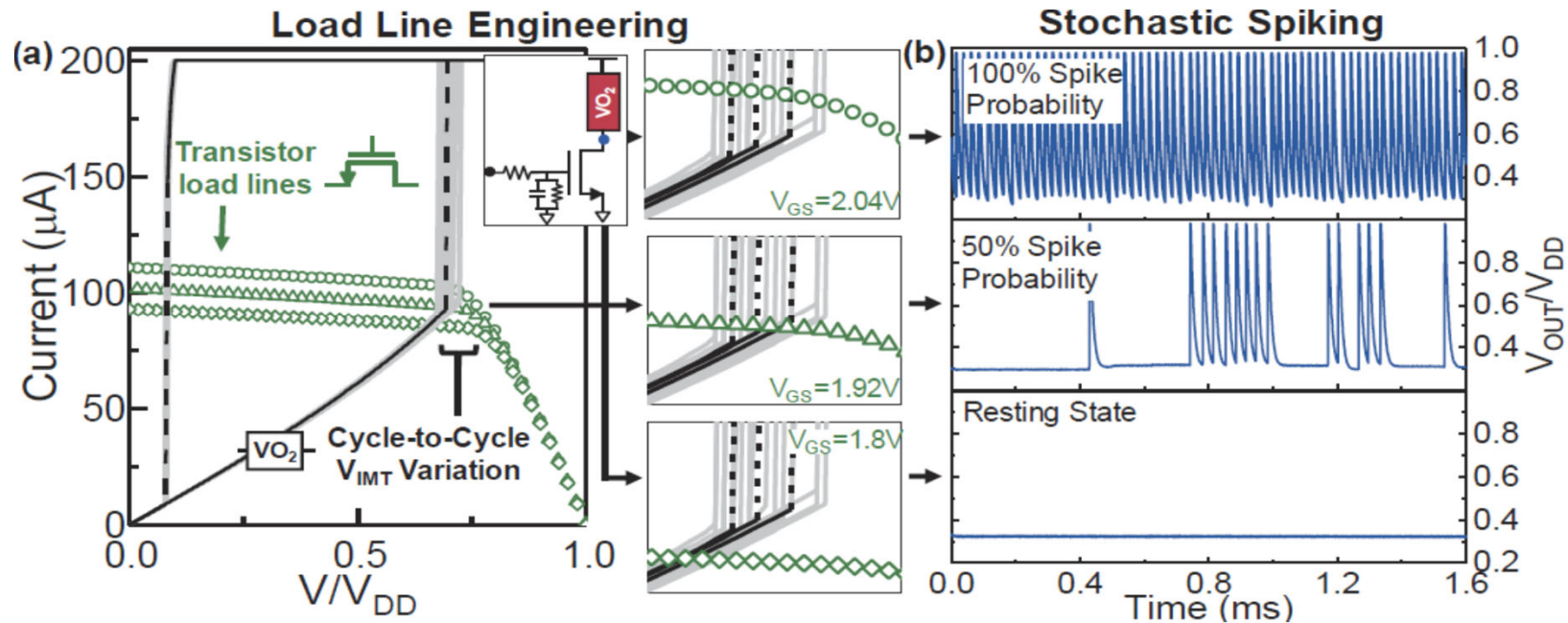


FIGURE 1 | Response to a stimulation principle: (A) Schematic of a single neuron, which can be divided into three functional parts: Dendrites, collect signals from other neurons; cell body (soma), the central processing unit of a neuron; axon, neuronal output stage. (B) Relationship between firing rate of a neuron and the strength of input stimulation reflecting the response to a stimulation principle as proposed by E. D. Adrian in 1926 (Adrian, 1926, 1928; Maass and Bishop, 2001).

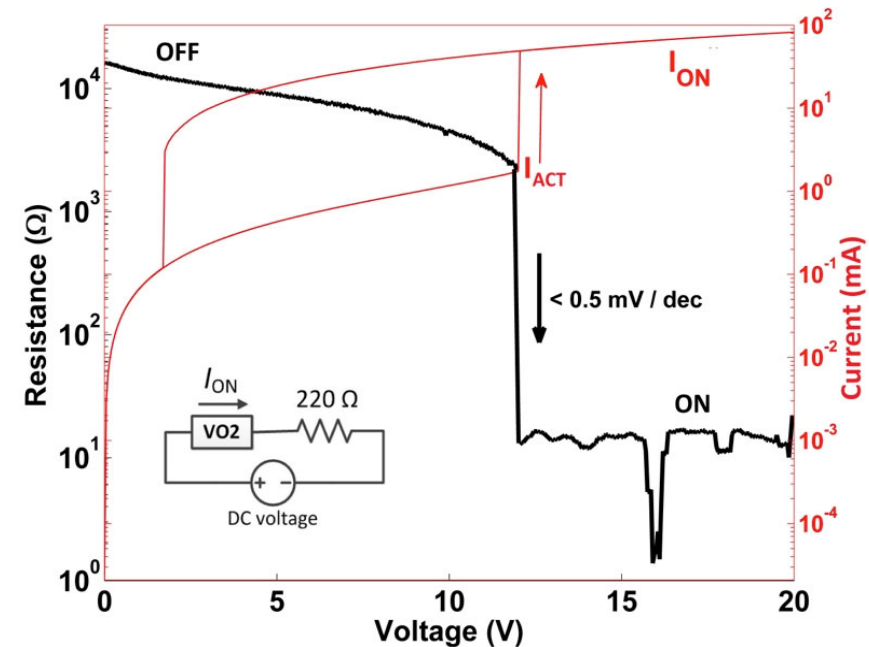
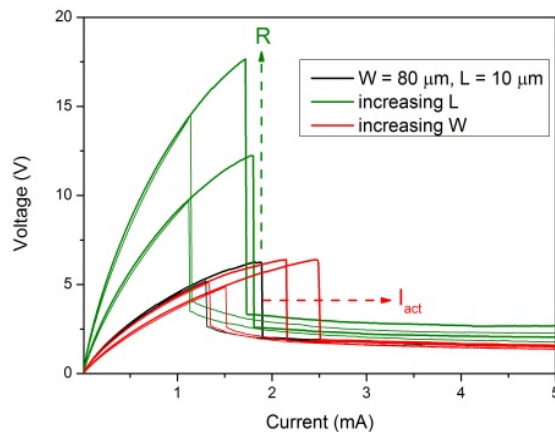
Example: MIT spiking neurons

Tuning the probability of spiking in a loaded VO₂-Transistor!



Example: Abrupt switching with steep slope

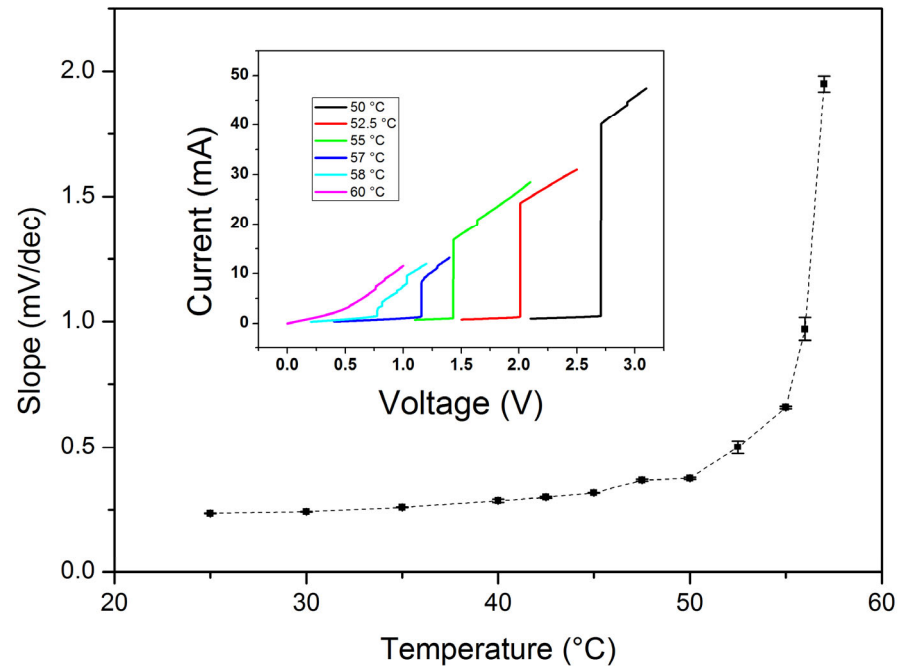
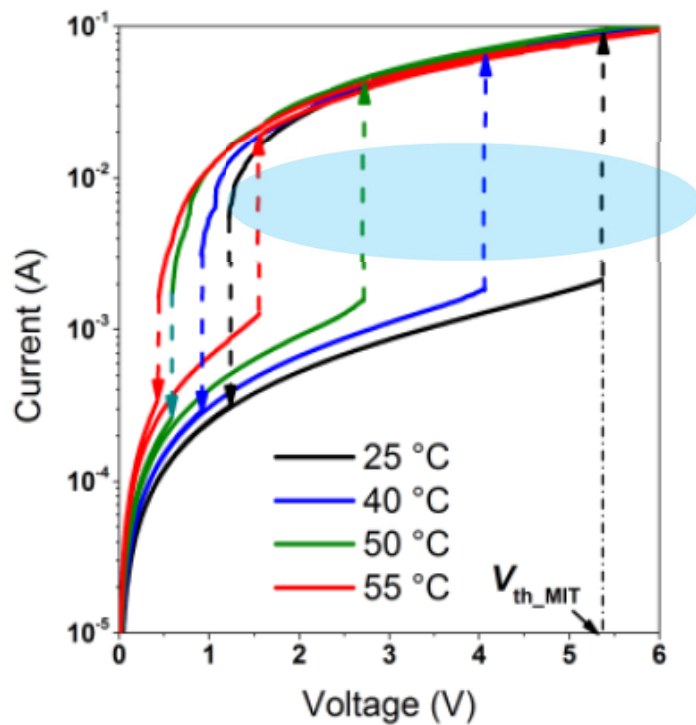
- Reconfiguration of three decades in resistance ($10^4 \Omega$ to 10Ω) achieved by E-MIT.
- Steep transition observed with a slope lower than 0.5 mV / dec .



- Voltage actuation in VO_2 -based abrupt electronic switches

W. A. Vitale et al., "CMOS-compatible abrupt switches based on VO_2 metal-insulator transition", *Ultimate Integration on Silicon Conference*, 2015.

Steep slope, $S < 10\text{mV/dec}$, characterization



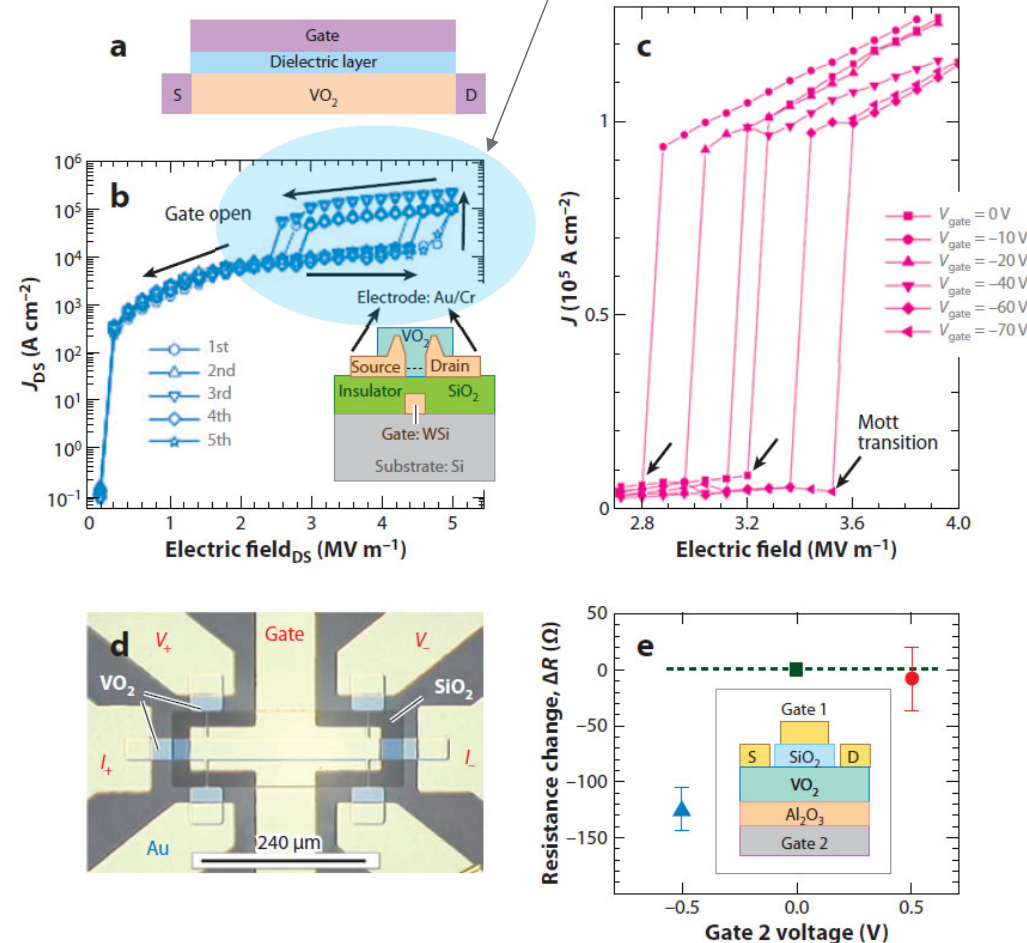
- Steep slope $< 1\text{ mV/dec}$ up to 57 °C
- Issue #1: hysteresis control.
- Issue #2: is just a diode, not a transistor.
- Issue #3: upper temperature $< 60\text{ °C}$

Three-terminal VO₂ electronic switch

Not in the desired region

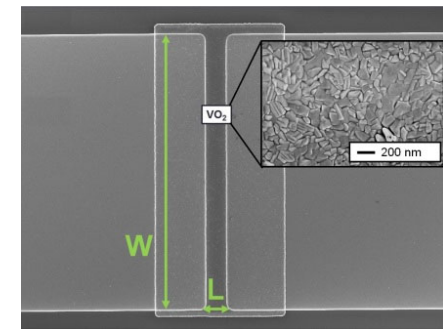
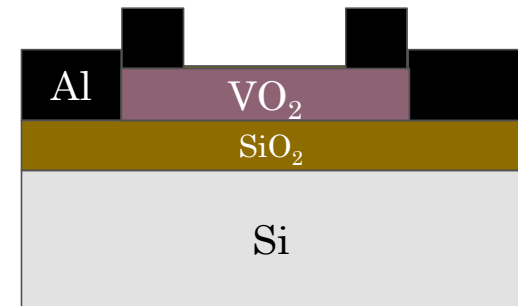
Three-terminal gated electronic switch devices utilizing MIT in VO₂.

- (a) An early proposed three-terminal gated VO₂ switch device.
- (b) Current density versus electric field applied on the VO₂ channel with the gate open at room temperature. The inset shows the three-terminal VO₂ device structure.
- (c) Current density versus electric field at room temp.
- (d) Optical microscopy image of the top view of a three-terminal VO₂ device
- (e) The effect of the back-gate (gate 2) voltage on the source-drain resistance of the VO₂ channel of a three-terminal VO₂ device with double-gate structure from the top view as shown in panel d.



Example: VO₂ Radio Frequency switch

1. LPCVD of 500 nm SiO₂ on silicon substrate.
2. Reactive magnetron sputtering of 360 nm VO₂ thin film at 490 °C using a V target.
3. Patterning of VO₂ with standard optical lithography and ion beam etching.
4. Lift-off of a 400 nm Al layer to define the contacts to induce E-MIT in VO₂.

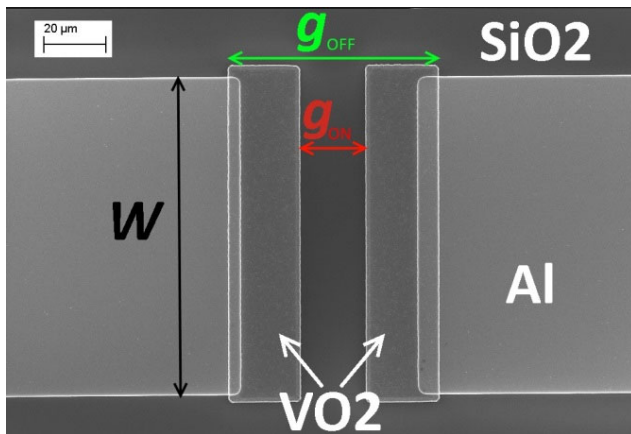


W. A. Vitale et al., “Growth optimization of vanadium dioxide films on SiO₂/Si substrates”, *40th Micro and Nano Engineering Conference*, Lausanne, Switzerland, September 22-26, 2014

W. A. Vitale et al., “Growth optimization of vanadium dioxide films on SiO₂/Si substrates for abrupt electronic switches”, *Microelectronic Engineering Journal*, 2015.

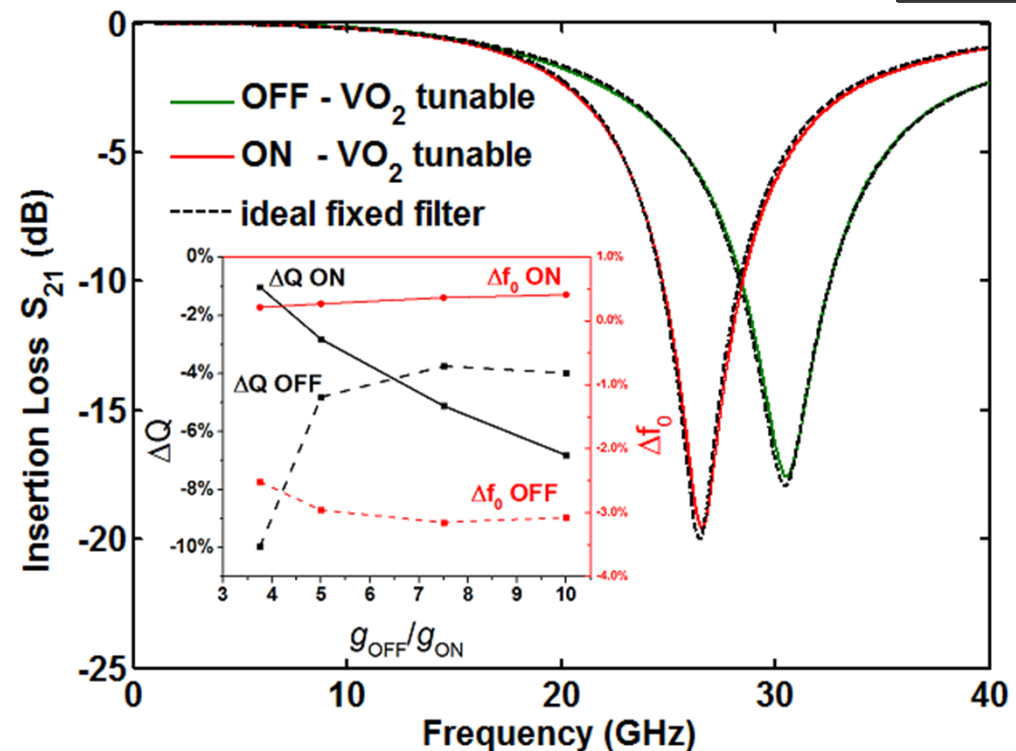
VO₂-based tunable RF filters with programmable insulating gaps

- VO₂-based RF devices for microwave tunable filters with low insertion loss.
- Design method adaptable to any planar coupled-resonator microwave filter.



- Idea VO₂-based tunable capacitive gap:

The equivalent insulating gap thickness and capacitance change when reversible MIT takes place.



- Comparison between VO₂ tunable filters and corresponding “ideal” fixed filters.

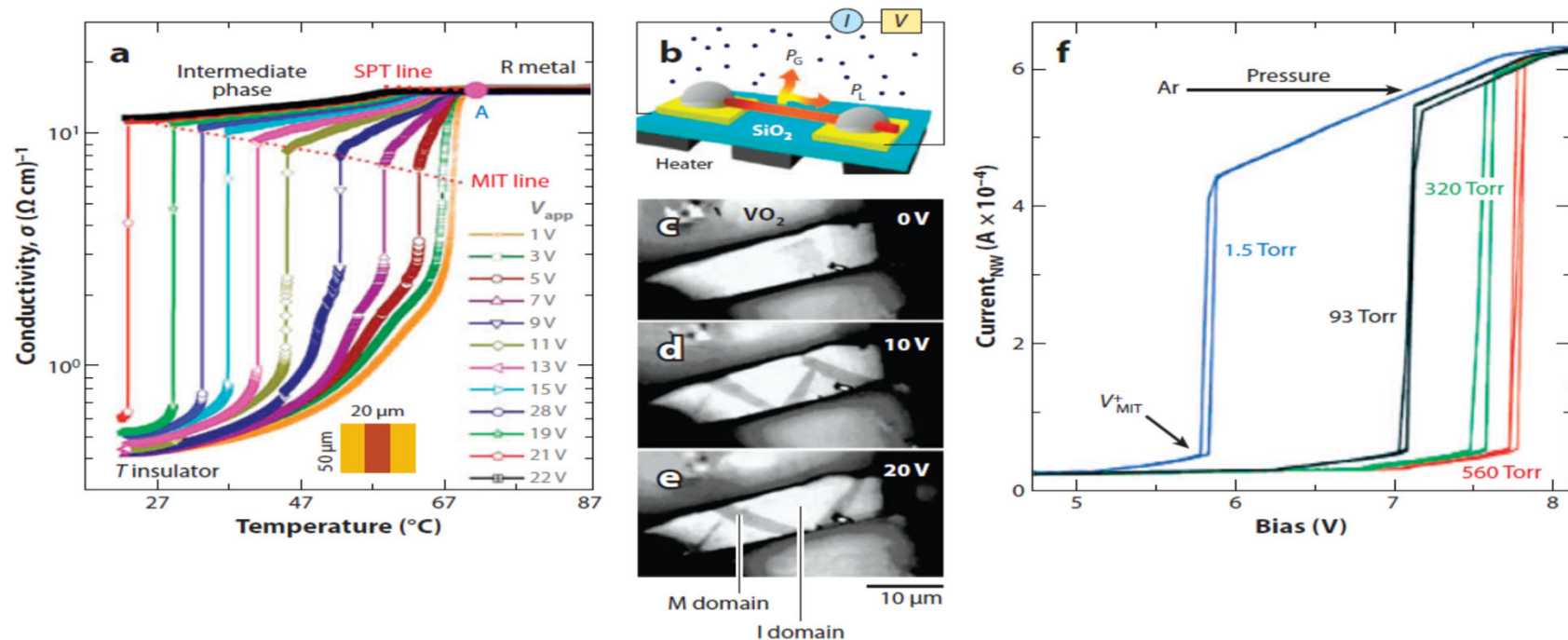
Example: Low power VO₂ gas sensors

Thermal sensor and gas sensor devices utilizing MIT in VO₂.

(a) A VO₂ thermal sensor device. Shown are the temperature and voltage dependency of the conductivity and the coplanar VO₂ device. The inset shows the device structure. SPT denotes structural phase transition.

(b) Schematic of a VO₂ nanowire gas sensor. *P_G* and *P_L* indicate heat flux dissipating into gas environment and metal contacts.

(c–e) Microscopic images of a VO₂ nanowire with increased self-Joule heating induced by the flowing current. (f) *I*-*V* characteristics of the VO₂ nanowire gas sensor device at different Ar pressures.



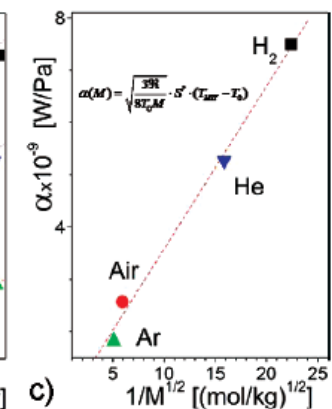
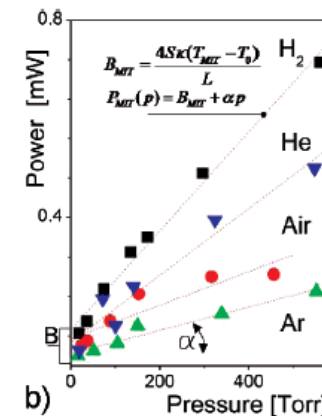
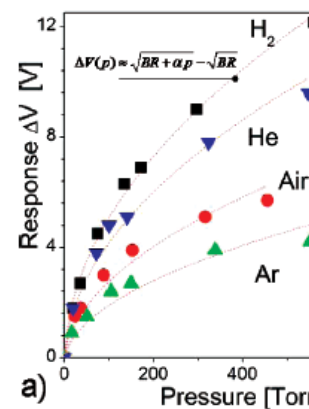
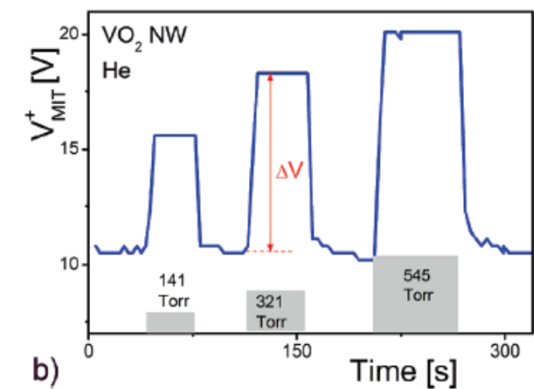
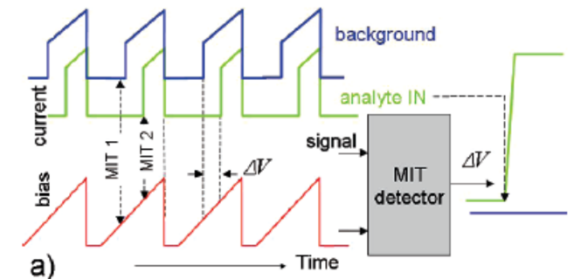
Low power VO₂ gas sensors

Principle:

- VO₂ NW acts as a preheated thermistor whose temperature (and thus resistance) depends on the delicate balance between the incoming Joule heat and outgoing heat fluxes.
- Any variations in the **thermal conductivity of the ambient gas** will be recorded as shifts in the transition voltage for MIT.
- **Significant advantage of this transduction principle: inherent independence on the chemical reactivity of a gas, what allows detection of chemically inert gases!**

$$S \equiv \frac{dV}{dp} = \left(\frac{\alpha R}{B/\alpha + p} \right)^{1/2}$$

Better sensitivity at low pressure and for lighter molecules (10⁻²Pa pressure change).



Conclusions

- A fast switch can be demonstrated utilizing metal-insulator transition in correlated oxides, with the ON and OFF states defined as a low-resistance, metallic phase and a high-resistance, insulating phase of the material, respectively. *Switching may be triggered with electronic, optical, thermal, or even with magnetic actuation.*
- VO₂ is one of the most promising researched MIT material because of its transition temperature near room temperature:
 - > 3-4 orders of magnitude with few volts actuation, sharp transition in resistivity has been reproduced with electrical actuation, allowing to introduce novel device structures for reconfigurable electronics.
- Room temperature Mott FETs with correlated oxides may be potential candidates for future computing elements. Utilizing a functional correlated oxide for information processing may lead to three-dimensional circuits and integration on polycrystalline or arbitrary substrates.
- Applications @ **short term: reconfigurable RF functions in GHz to THz range.**
- Applications @ **long term: steep slope electronic switches (with hysteresis: can serve neuromorphic computing).**